BIOMASS AND BIOENERGY 49 (2013) 333–340

Available online at www.sciencedirect.com

SciVerse ScienceDirect

http://www.elsevier.com/locate/biombioe

BIOMASS & BIOENERGY

Performance evaluation of three types of forced draft cook stoves using fuel wood and coconut shell

P. Raman, J. Murali, D. Sakthivadivel, V.S. Vigneswaran*

The Energy and Resources Institute, Darbari Seth Block, IHC Complex, Lodhi Road, New Delhi 110 003, India

A R T I C L E I N F O

Article history:
Received 18 July 2011
Received in revised form
8 December 2012
Accepted 19 December 2012
Available online 14 February 2013

Keywords:
Biomass gasifier
Forced draft cook stoves
Heat transfer
Thermal efficiency
Specific fuel consumption

A B S T R A C T

Many cook stove programs implemented in South Asia and Africa were aimed at reducing fuel wood consumption and pollutants through the use of improved cook stoves. The research work presented in this paper is focused on evaluation of improved cook stoves with respect to thermal efficiency and emission levels. Since the type of biomass fuel varies in different geographical regions, the improved cook stoves must be compatible to use different types of fuel. The present research work is aimed at evaluating three types of forced draft cook stove with two types of biomass fuels. Water boiling tests were conducted to evaluate the stove performance with respect to efficiency and fuel flexibility. The findings of the study are used to evaluate the stove's performance with respect to fuel flexibility, efficiency and user acceptance. The performance results of three types of forced draft stoves tested with fuel wood and coconut shell are presented in this research paper.

1. Introduction

Globally about 2.4 billion people i.e. about 35% of world population depended on traditional fuels like wood, charcoal, agricultural residues and cattle dung to meet their cooking and heating requirements. It is expected that by 2030 another 200 million will be added to the existing number of people using traditional fuels for cooking and heating [1]. Each family requires about 2 tonnes of fuel wood per year [2] and this wood is mostly collected by women and children [3]. Women and children are highly affected by indoor air pollution caused due to poor biomass cooking technology. They are exposed to Respirable Suspended Particulate Matter (RSPM) which is 20 times more than the acceptable level [4]. Indoor air pollution caused by the use of traditional cook stoves resulted in two million deaths annually [5]. It has also been found that 730 million tonnes of biomass are burned every year in developing countries, which accounts for the emission of one billion tonnes of carbon dioxide into the atmosphere. The combustion of biomass can be considered as carbon neutral only when it is harvested from a sustainable source. As most of this biomass are harvested unsustainably, they led to deforestation and global warming. It is necessary to develop a cook stove which works with high thermal efficiency and emits less pollutants.

Much development has occurred in the cook stove design, during 1980's and early 1990's to examine heat and combustion efficiency of the cook stoves. The improved cook stoves were generally made using locally available materials like clay and sand. A chimney was introduced to the improved cook stoves to vent out the pollutants generated due to incomplete combustion. As these stoves were built by local artisans, the life of these stoves was much lower than their expected life span of two years. It was only during the late

* Corresponding author. Tel.: +91 9894155536.
E-mail addresses: raman03@gmail.com (P. Raman), muralijana@gmail.com (J. Murali), sakthi2energy@gmail.com (D. Sakthivadivel), vignesrahul@gmail.com (V.S. Vigneswaran).
0961-9534/$ – see front matter
http://dx.doi.org/10.1016/j.biombioe.2012.12.028

1990's and early 2000's stoves were made using durable materials thereby increasing their life span. However, the efficiency of these stoves was still lower than the efficiency of stoves which uses LPG and kerosene as a fuel. It was found that the efficiency of kerosene and LPG stoves was higher when compared to biomass stoves because they achieve better combustion and operate at near stoichiometric conditions [6]. The operation of the stove near stoichiometric condition leads to the formation of product gas at peak temperature. This temperature determines the amount of heat received by the bottom area of the vessel. Hence, the stove operates at its maximum potential when the air–fuel ratio is maintained near stoichiometry. This also helps to reduce the carbon monoxide emissions. The lower combustion temperature of biomass helps to limit the emissions of NO_x naturally. Limiting the velocity of the air supply will limit the particulate carryover. The fuel property, the amount of air supply for combustion and its distribution determines the efficiency and emission levels of a cook stove.

Forced draft stoves are considered as a viable option to overcome these problems [7]. The fuel is burnt in gasifiers in four stages namely drying, pyrolysis (carbonization), char gasification and gas combustion. The moisture content of the fuel is removed during the drying process leaving behind the dry fuel; the amount of heat energy loss occurring during this process depends upon the moisture content of the fuel. It requires about 3.21 MJ of energy to remove 1.0 kg of moisture present in the fuel [8]. In the forced draft cook stoves, the biomass fuel fed into the combustion chamber is dried, pyrolyzed and converted into a gaseous fuel through the partial combustion process. Combustion of gaseous fuel is highly efficient and it has the potential to save about 40% of fuel wood when compared to traditional cook stoves. Moreover the pollutant emitted from the forced draft stove is 90% lower than the traditional cook stoves [9]. This paper also reports that while conducting Water Boiling Test (WBT), a forced draft stove emits 6 g of CO against 50 g by a traditional stove. Similarly while conducting the WBT; the forced draft stove emits an average of 143 mg of particulate matter as against 1500 mg in the case of traditional stoves.

This study evaluated the performance of three stoves namely Oorja-Plus, Philips and TERI's cook stoves. The Oorja-Plus stove was designed by the Indian Institute of Science, Bangalore and promoted by the BP Energy India Limited. The BP Energy India Limited has disseminated over 475 000 Oorja-Plus stoves across thousands of villages and urban areas in the states of Maharashtra, Karnataka, Tamil Nadu and Andhra Pradesh. The Philips turbo stove was developed initially by Philips Research, but later it was transferred to Philips Domestic Appliances and Personal Care. Recently TERI has developed a turbo stove, which is under dissemination across India.

2. Methodology

2.1. *Geographical location of the study region*

Kerala state is located in the Southwestern tip of the Indian peninsula. The Kerala state lies between 8°17′–13°30′ N latitude and 74°52′–77°25′ E longitude. It forms a 38,864 km^2 linear stretch of land, along the Southwest coast of India. Rainy days in Kerala vary from 120 to 140 days in a year. The State receives an average rainfall of 3107 mm a year. In most of the regions of Kerala, fuel wood and coconut husk are commonly used as fuel for cooking. Each coconut tree yields an average of 70–100 coconuts per year which in turn will provide about 21 kg–30 kg of coconut shell per year. Coconut shell is sold in the fuel wood market itself with the local name of '*Serattai*'. Cost of coconut shell is 70 \$ t^{-1}and cost of the fuel wood is100 \$ t^{-1}.

2.2. *Source of fuel*

The study was conducted at Trivandrum in Kerala state. In Kerala state, coconut shell (*Cocos nucifera*) is to be found in the fuel wood market with the major wood species being Mango (*Mangifera indica*). Both of these fuels were used in the stoves for the study of performance analysis. The biomass fuel used in the study was purchased from the fuel wood market located in the city of Trivandrum. The fuel wood market is one of the largest energy markets in India with over 12 million persons are involved in the collection, processing and selling of fuel wood [10]. The fuel wood market is very much scattered and unorganized, even though it provides over 80% of the supply from recognized sources, with less than 20% coming from unidentified sources [11]. In rural areas the fuel wood is collected and sold by women with the wood coming from many different age classes of trees. As an informal sector it does not follow conventional business practices, with much of the cost being non-financial.

2.3. *Fuel characteristics*

Three stoves were tested by using wood chips and coconut shell as fuel, whose net calorific value was about 17.15 MJ kg^{-1} and 22.02 MJ kg^{-1} respectively. The fuel wood and coconut shell were purchased from the local fuel wood market. The fuel wood and coconut shell were purchased from the same lot to avoid any variation in the fuel characteristics. The fuel wood was chopped manually to an average dimension of 4.7 cm × 1.4 cm × 1.0 cm. The coconut shell used has the average dimension of about 7.2 cm × 4.2 cm × 0.2 cm. It is essential to admit that source, quality and moisture level of the fuel have an effect on the stove performance. Hence all stoves were tested using the same fuel. At the time of purchase, mass fraction of moisture content of wood chips and the coconut shell was measured at 0.18 and 0.22 respectively. The moisture content of the fuel purchase was observed higher than the normal conditions due to the prolonged monsoon season in that region. The fuel was chopped into small pieces and air dried. After drying, the mass fraction of moisture content of both the fuel dropped to 0.07.

The proximate and ultimate analysis of the fuel, used during the experiment, is given in Table 1. The results of the proximate and ultimate analysis were on dry basis. The results of the fuel wood samples were based on the analysis obtained from the lab. The results for coconut shell samples are referred from the guidebook for national certification examination for energy managers and energy auditors [12].

2.4. Water Boiling Test (WBT)

It may be difficult to evaluate the performance of cook stoves in the field due to the difference in fuel use, type of pot, operator effect and the type of food cooked. The effects of some of these parameters can be investigated by using the WBT to develop stoves that can perform well under different field conditions. However other variables cannot be easily quantified, such as the common practice of leaving the fuel in the stove to smolder when finished cooking. Therefore the performance of the stoves was analyzed by using the Water Boiling Test (WBT) Version 3.0 [13]. This modified version of the WBT designed to simulate the actual cooking process to understand the rate of energy transferred from the fuel to the cooking pot. The WBT includes three phases. In the first phase, 5.0 kg of water was made to boil in a standard pot without lid, starting with the stove at room temperature. During the second phase, again the fresh water was boiled starting with a hot stove to estimate the differences in performance between the cold and hot start. In the third the tester simmers the heat input to maintain the water approximately 3 °C below boiling point for 45 min. In between, these three phases, the wood, water and charcoal were weighed by removing and extinguishing the fuel. These measurements were used to evaluate the stove's performance at high and low power. The most important parameter obtained from the WBT test was specific fuel consumption, which is the amount of fuel spent to produce 1.0 kg of boiled and simmered water for a given period. It has been found that specific fuel consumption is a strong indicator of stove performance than the simple measurement of thermal efficiency. As per the WBT protocol, lids were not used to close the pots. The fuel was carefully fed for constant burning, and air spaces were left between pieces of fuel to allow better combustion.

2.5. Estimation of specific fuel consumption and efficiency

Specific fuel consumption is mainly used to find out the fuel spent to complete the WBT. The specific fuel consumption rate is corrected for the initial temperature of the water, the moisture content of the fuel, the energy expended to evaporate the moisture of the fuel and quantity of water evaporated [9]. Specific fuel consumption (SFC) is the amount of fuel required to boil 1.0 kg of water. The specific fuel consumption rate is calculated using the following equation:

$$\mathrm{SFC} = \left\{ \frac{[75/(T_{\mathrm{boil}} - T_{\mathrm{start}})] \times [\mathrm{Mass}_{\mathrm{mw}} \times (1 - \mathrm{MC}) - \mathrm{Mass}_{\mathrm{fwe}})] - 1.5 \times \mathrm{Mass}_{\mathrm{char}}}{\mathrm{Mass}_{\mathrm{water\ remaining}}} \right\} \quad (1)$$

where SFC represents the specific fuel consumption

MC represents moisture content of the fuel in percentage
$\mathrm{Mass}_{\mathrm{mw}}$ represents mass of the moist wood
$\mathrm{Mass}_{\mathrm{fwe}}$ represents mass of the fuel wood used to evaporate water
$\mathrm{Mass}_{\mathrm{char}}$ represents mass of the remaining charcoal after conducting WBT
Factor of 75 is the standard temperature increases from starting temperature to local boiling temperature

Mass of fuel wood used to evaporate the water can be written using the following equation:

$$\mathrm{Mass}_{\mathrm{fwe}} = \left\{ \frac{[\mathrm{Mass}_{\mathrm{mw}} \times \mathrm{MC} \times 4.186 \times (T_{\mathrm{boil}} - T_{\mathrm{room}})] + 2257}{\mathrm{Net\ Calorific\ Value}_{\mathrm{fuel}}} \right\} \quad (2)$$

where T_{boil} represents the local boiling temperature of water

T_{room} represents the air temperature in the room where the test is conducted
$\mathrm{Net\ Calorific\ Value}_{\mathrm{fuel}}$ represents the higher heating value of the fuel on dry basis

The specific fuel consumption (SFC) is the preferred parameter emerging from the WBT, when compared to thermal efficiency, because even a stove that is very slow to boil the water will evaporate a lot of water in the process, resulting in higher thermal efficiency. But this may not be acceptable from a user perspective due to the time taken for cooking. Specific fuel consumption includes fuel used for boiling and simmering. Thus the specific fuel consumption rate can be combined as one metric for both high and low power phases.

Table 1 – Ultimate and proximate analysis of fuel wood and coconut shell.

Component	Unit	Fuel wood	Coconut shell
Proximate analysis			
Ash	Mass fraction percentage	1.76	4.09
Volatile matter	Mass fraction percentage	76.75	71.95
Fixed carbon	Mass fraction percentage	21.49	23.96
Ultimate analysis			
Carbon	Mass fraction percentage	48.00	54.52
Hydrogen	Mass fraction percentage	9.23	6.05
Nitrogen	Mass fraction percentage	1.42	0.69
Oxygen	Mass fraction percentage	41.35	38.74

3. Descriptions of the stoves tested

Forced draft stoves tested in the study works on the principle of biomass gasification. The combustion of gaseous fuel is clean when compared to solid fuels like fuel wood. With the air input gaseous fuel forms a uniform combustible mixture and provides clean combustion results in higher efficiency. The device that enables conversion of solid fuel to gaseous fuel by a thermochemical conversion process is known as gasifier. This process involves sub-stoichiometric high temperature oxidation and reduction reactions between the solid fuel and an oxidant. These high temperature combustible gases are burnt at the top of the combustion chamber with additional air (secondary air) supply. An important factor of this mode of operation is maintaining a fixed ratio between the amounts of combustible gases produced and the primary air supplied for gasification. The fuel consumption increases with the increase in primary air supply. This results in an increase of the power output. Therefore the heat input of the cook stove is directly proportional to the supply of the primary air. The gas produced from biomass is called as producer gas, which consists of combustible gases like carbon monoxide, hydrogen, methane, and some higher hydrocarbons. These gases are burnt to carbon dioxide and H_2O using the secondary air which is supplied at the top of the combustion chamber. The flame temperature of the gasifier stove is in the range of 1000 °C–1100 °C. The flame temperature of the conventional stove is in the range of 700 °C–800 °C. The higher the flame temperature will result into the increased heat transfer rate, thus making the gasifier stoves work at higher efficiency than the traditional stoves.

Performance evaluation of three gasifier cook stoves with two types of biomass fuel was carried out in this study. The name of the stoves tested with different types of biomass fuel is;

i. Oorja-Plus .A view of the Oorja-Plus stove is shown in Fig. 1.
ii. Philips Stove. A view of the Philips stove is shown in Fig. 2.
iii. TERI's cook stove. A view of the TERI's cook stove is shown in Fig. 3.

3.1. *Construction and technical features*

Technical specifications and materials used in the fabrication of cook stoves influence its performance. Technical parameters, material used in the fabrication of the stoves are listed in Table 2.

3.1.1. *Combustion chamber*

The inner wall of the combustion chambers is made of ceramic composition material. This is used to sustain the heat produced during the combustion, thereby increases the life span of the combustion chamber. Its outer wall is made of stainless steel. The primary and the secondary air were supplied to these stoves by using a fan placed below the combustion chamber. In the case of TERI's cook stove, 8 numbers of holes with a diameter of 4.5 mm is provided at the bottom of the combustion chamber for the supply of primary air. At the top of the combustion chamber 26 numbers of holes with a diameter of 3 mm is provided for the supply of secondary air.

3.1.2. *Primary and secondary air inlet*

The primary air gets into the firebox and it is uniformly distributed through the grate at the lower portion of the combustion chamber. The hot gas produced from the partial combustion of the fuel in the firebox is carried upward towards the top of the combustion chamber. The gas produced is then burnt at the top of the combustion chamber with a supply of secondary air to achieve clean combustion which results in higher efficiency. The air entering into the combustion chamber can be controlled by adjusting the fan speed. In TERI's and Philips cook stoves the fan speed can be gradually regulated from maximum to minimum power. Hence it is

Fig. 1 – Oorja-Plus forced draft stove.

Fig. 2 – Philips forced draft stove.

Fig. 3 – TERI's forced draft stove.

convenient for the user to control the burning rate of the fuel and the temperature in the combustion chamber by controlling the air supply. However in the case of Oorja-Plus stove, the fan can be operated only in two levels of speed (minimum or maximum) thus making it difficult for the user to control the burning rate of the fuel and the temperature in the combustion chamber.

3.1.3. Grate

The grate of these three cook stoves is made up of cast iron. A removable grate is used in Oorja-Plus stoves, on the other hand the grate of the other two stoves is fixed to the combustion chamber. The grate is used to drastically improve the combustion quality and the burning rate by providing adequate air supply. In the case of TERI's and Philips stoves primary air is supplied through the holes present in the grate, whereas in the Oorja-Plus stoves the air is supplied through the grills.

3.1.4. Forced draft created using a DC fan

In the case of TERI's and Philips cook stoves, the fan is fixed under the grate, In the case of Oorja-Plus stove, the fan is attached at a right angle to the grate. This helps to protect the fan from the heat generated in the combustion chamber. A 1.8 W fan was used in the Oorja-Plus stove and powered by a battery cell of 1.5 V DC. Philips and TERI's cook stoves use a fan which operates at 12 V DC. The 12 V DC fan operates in the range of 3 W–6 W depending on the heat input requirement. Battery used to drive the Oorja-Plus stove lasts for 5–6 cooking cycles and it takes about 30 min to recharge. The battery charger is supported by circuitry that boosts the voltage and starts warning the user with a beep sound when the voltage drops to 0.7 V providing the user ample time to finish the cooking. In the Philips cook stove, the fan is driven by a rechargeable battery, which is built-in along with the stove and is provided with a charger. In the TERI's cook stove, the fan is driven by a battery, which can be recharged either by connecting it to the power supply or to a solar panel. The presence of solar panel may help users to overcome charging problem in the rural areas where the grid is absent.

4. Results and discussions

Three different stoves were tested in the laboratory and the results were tabulated. Fuel used to test the stoves was also provided. Efficiency of these three stoves was estimated by using the WBT protocol. Fuel burning rate and firepower were also calculated. The average values of efficiency, fuel burning rate and firepower produced for the cold start, hot start and simmering are presented.

Table 2 – Technical parameters and specification of the forced draft stoves.

Serial number	Component	Governing parameters	Key specifications
1	Blower to supply the required air	Distribution and control of primary and secondary air supply	Clean and smokeless combustion with high efficiency
2	Firebox or fuel combustion chamber	Fuel holding capacity, material of fabrication, ash space and air distribution ports	Burning rate and duration of operation. High temperature resistant long durable firebox
3	Comfortable handling, cold surface temperature and stable structure	Insulation of firebox, preheated air chambers	Safe and user friendly
4	Power level control	Liner variable electronic control for adjusting the power	Flexibility to control the flame level by varying the input power
5	Service provisions	Rugged spares and easy access to service components	Service facility
6	Esthetic and strong vessel support	Material selection and geometry optimization	Convenience and comfort cooking solutions
7	Cost optimization	Material optimization	Increased affordability

Table 3 – The efficiency of the gasifier stoves with different fuels.

Fuel	Stove	Fuel burning rate (g min^{-1})	Efficiency (%)	Firepower (W)
Wood chips	Oorja-Plus	16.6	32.3	5307
	Philips	23.4	38.7	7475
	TERI	22.8	39.3	7276
Coconut shell	Oorja-Plus	19.0	35.3	6794
	Philips	27.0	32.7	9603
	TERI	29.9	36.0	8153

4.1. *Performance test and burning rate*

The burning rate of the stoves varies with the fuel used. The results indicate that the fuel used in TERI's stove had a higher burning rate than other cook stoves. This is mainly due to the improved supply of primary and secondary air into the combustion chamber using the fan. The average fuel burning rate of TERI's stove was 23 g min^{-1} while using wood chips as fuel. While using wood chips the average fuel burning rate of Oorja-Plus and Philips stoves were 23 g min^{-1} and 16 g min^{-1} respectively. The same pattern was observed while using coconut shell as fuel. The average fuel burning rate of TERI's, Oorja-Plus and Philips cook stoves was 30 g min^{-1}, 19 g min^{-1} and 27 g min^{-1} respectively.

4.2. *Performance efficiency of stoves*

When wood chips were used as the fuel, the thermal efficiency of the Oorja-Plus stove was found constant during three phases of tests. The thermal efficiency of the Oorja-Plus stove was estimated at 32% during cold start and simmering phases. During the hot start phase the thermal efficiency the stove was recorded at 33%. While using coconut shell as fuel the efficiency of the stove during cold start and hot start were dropped down to 29% and 29.3% respectively. But the thermal efficiency of the stove during the simmering process was increased to 47%. Hence it was observed that the thermal efficiency of the stove during hot start and the cold start process decreases with increase in calorific value of the fuel, but the reverse occurs during the simmering process. Test results of the thermal efficiency of the gasifier stoves are presented in Table 3.

Table 4 – Specific fuel consumption of the forced draft cook stoves tested with different fuels.

Stove	Specific fuel consumption to heat water (g kg^{-1})	
	Wood chips	Coconut shell
Oorja-Plus	98.3	132.3
Philips	162.3	162.7
TERI	124.6	122.3

Instead of fuel wood, when coconut shell was used as the fuel, the thermal efficiency of the Philips cook stove decreases by 5%–7% during all the three phases. Whereas TERI's cook stove's thermal efficiency decreases by 3%–7% while using coconut shell as fuel. A 7% decrease in thermal efficiency was observed during the hot start process. During other processes of WBT it drops to 3%. Thus TERI's cook stove has similar efficiency irrespective of the fuel used.

4.3. *Specific fuel consumption*

Fig. 4 shows the specific fuel consumption of all three cook stoves during cold start, hot start and simmering phases (in MJ kg^{-1}). The specific fuel consumption of TERI's cook stove was recorded lower than the other two stoves during the high power cold start and hot start processes while using wood chips as fuel. On the other hand, the specific fuel consumption of Oorja-Plus stove is lower than the other two stoves while using coconut shell as the fuel. The specific fuel consumption of TERI's cook stove increases with increase in calorific value. However the specific fuel consumption of the Oorja-Plus stove decreases with increase in calorific value. The specific fuel consumption of the Philips stove remains same irrespective of the fuel used. Specific fuel consumption of the stoves tested with different fuels is provided in Table 4. Specific fuel consumption of wood chips and coconut shell in all the cook stoves is shown in Figs. 4 and 5 respectively. Efficiency versus firepower with wood chips is shown in Fig. 6. Efficiency versus firepower with coconut shell is shown in Fig. 7.

From Figs. 6 and 7, it can be found that the firepower of the cook stove increases with the increase in calorific value of the fuel used. But the efficiency of the TERI's and Philips cook stoves decreases with increase in firepower, thus indicating that a lot of energy is lost. On the other hand, the efficiency of

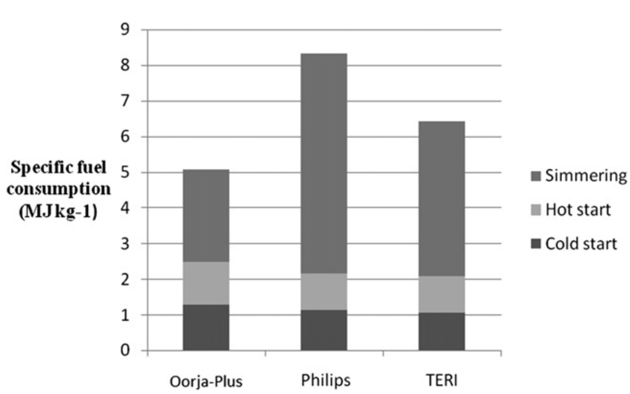

Fig. 4 – Specific fuel consumption of wood chips.

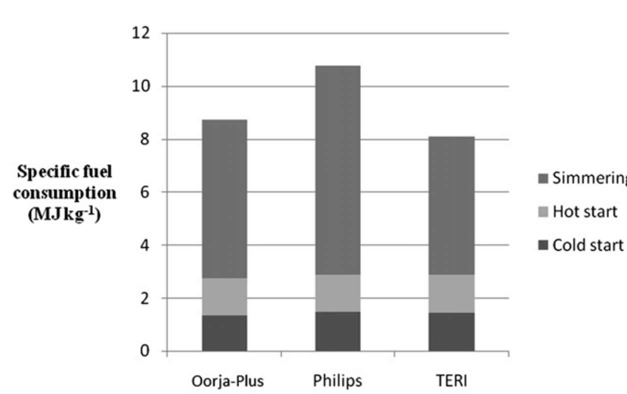

Fig. 5 – Specific fuel consumption for coconut shell.

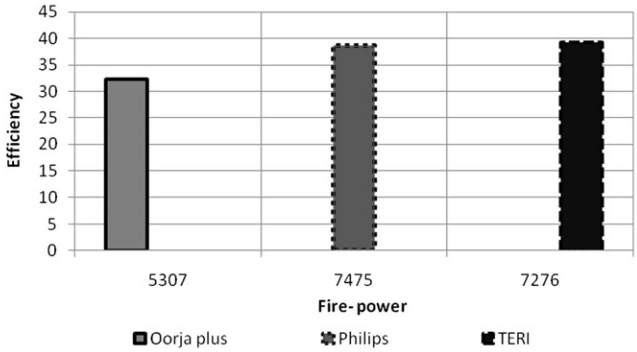

Fig. 6 – Efficiency versus firepower with wood chips.

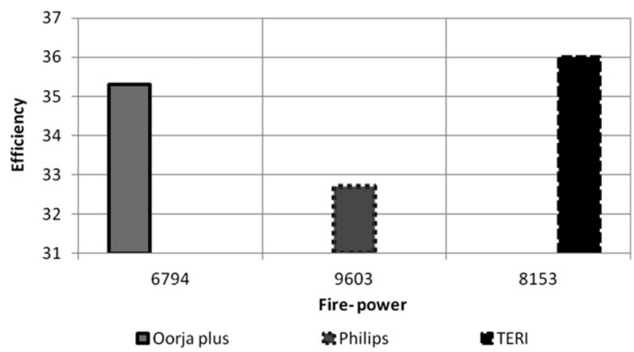

Fig. 7 – Efficiency versus firepower with coconut shell.

the Oorja-Plus stove increases with an increase in firepower. Thus, the Oorja-Plus stove operates better when using coconut shell as the fuel when compared to wood chips. But reverse happens in case of Philips and TERI's cook stoves.

Forced draft cook stove increases both heat transfer rate and combustion efficiencies simultaneously. Hence forced draft stoves must be carefully designed and optimized for higher efficiencies. Simple changes in the stove design can have larger impacts, such as density (insulation properties) of the combustion chamber, height of the stove, fuel preparation, and the gap between the base of the vessel and firebox. Laboratory testing is useful in performance evaluation and customization of cook stoves. Forced draft stoves can provide remarkably clean burning when used with the right fuel and adequate air supply. These types of cook stoves, helps move biomass up in the energy ladder and making it closer to the liquid fuels. However users at large may find the fuel processing as a constraint in the adoption of these cook stoves. This constraint needs to be addressed for large scale adoption of forced draft cook stoves.

5. Conclusions

Thermal efficiency and specific fuel consumption of the Philips cook stove remained almost constant irrespective of the fuel used. On the other hand, the specific fuel consumption of TERI's stove increases while using coconut shell as the fuel. But the reverse happens in case of the Oorja-Plus stove. Though the firepower produced by Philips stove is higher than that of other two stoves, their thermal efficiency is low, which indicates that a large amount of the heat produced is lost. The turn down ratio of TERI's cook stove is high when compared to other stoves while using both fuels. It shows that the power produced by TERI's cook stove can be varied from maximum to minimum value gradually.

Acknowledgment

We are grateful to Dr. R. K. Pachauri, Director General of TERI for his continuous encouragement to conduct research on clean combustion cook stoves. We also would like to thank Mr. Amit Kumar and Mr. Ibrahim Hafeez Rehman, (both Directors of TERI) for providing valuable support to conduct the research.

Nomenclatures

$Mass_{char}$ mass of the remaining charcoal after conducting WBT
$Mass_{fwe}$ mass of the fuel wood used to evaporate water
$Mass_{mw}$ mass of the moist wood
$Mass_{water\ remaining}$ mass of water remaining in the pot at the end of the test
MC mass fraction of moisture content of the fuel on wet basis
Net Calorific $Value_{fuel}$ net calorific value of the fuel on dry basis
NO_x oxides of nitrogen
SFC specific fuel consumption
T_{boil} the local boiling temperature of water
T_{room} the air temperature in the room where WBT is being conducted
T_{Start} starting temperature of the water

REFERENCES

[1] IEA. World energy outlook 2002. Paris: International Energy Agency, OECD; 2002. p. 47.
[2] World Bank. Household cook stoves environment, health, and climate change: a new look at an old problem. Washington DC: International Bank for Reconstruction and Development; 2011. p. 80.
[3] Laximi V, Parikh J, Karmakar S, Dabrase P. Household energy, women's hardship and health impacts in rural Rajasthan, India: need for sustainable energy solutions. Energ Sustain Dev 2003;7(1):50–68.
[4] WHO. Air quality guidelines global update 2005. Copenhagen: World Health Organization; 2005. p. 484.
[5] WHO and UNDP. The energy access situation in developing countries: a review focusing on the least developed countries and sub-saharan Africa. New York: United Nations Development Program; 2009. p. 130.
[6] Mukunda HS, Shrinivasa U, Dasappa S. Portable single-pan wood stoves for high efficiency. Sadhana 1988;13:237–70.

[7] Mukunda HS, Dasappa S, Paul PJ, Rajan NKS, Yagnaraman M, Ravi kumar D, et al. Gasifier stoves – science, technology and field outreach. Curr Sci 2010;98(5):627–38.
[8] Roth C. Micro gasification: cooking with gas from biomass. 1st ed. Eschborn: GIZ HERA – Poverty-Oriented Basic Energy Service; 2011. p. 100.
[9] McCarty N, Still D, Ogle D. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energ Sustain Dev 2010; 14(3):161–71.
[10] Richard M. New story of old fuel wood. India: Live Mint Wall Street Journal [Cited 2012 Nov 28]. Available from: http://www.livemint.com/Opinion/thIfyhtVcthyi9OQlT48eL/New-story-of-old-fuelwood.html; 2009.
[11] Nitin S. Fuel wood market. Available from: Source of biomass fuel for cooking in rural India [article on the Internet]. India: Times of India [Cited 2012 Nov 28]. Available from:, http://articles.timesofindia.indiatimes.com/2011-06-05/india/29622828_1_illegal-trade-forests-loaders; 2011.
[12] Energy efficiency in thermal utilities, guide book for national certification examination for energy managers and energy auditors [guide book 2]. India: Bur Energy Efficiency, Government India [Cited 2012 Nov 27]. Available from: http://www.emt-india.net/Book2/Book2.htm.
[13] Bailis R, Ogle D, MacbCarty N, Still D. The water boiling test (WBT) version 3.0. Household energy and health program. Shell Foundation; 2007. p. 38.